IUPAP Commission 10

Condensed Matter

Working Group on Nanoscience

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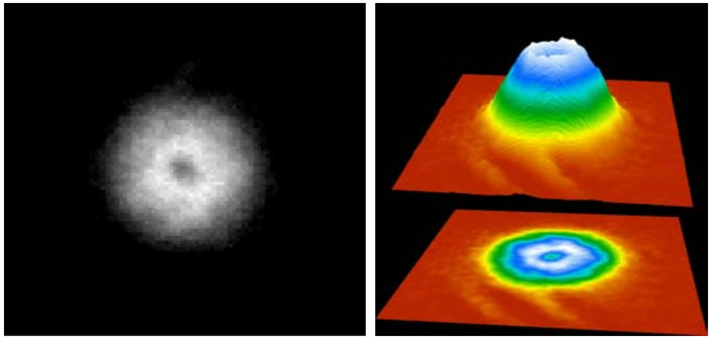
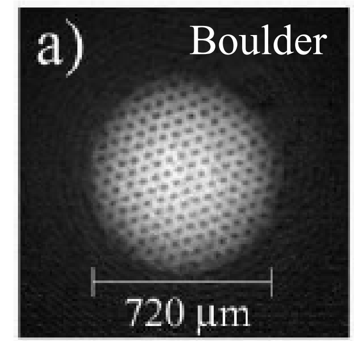
1. “Nanoscience systems” with cold atoms

small size + complexity + strong correlations

Bose gases in fast rotation





Isotropic harmonic trapping in the *xy* plane with frequency ω

Hamiltonian in the rotating frame: $H-\Omega L_z$

Choose Ω close to ω

$$H=\frac{p^2}{2M}+\frac{1}{2}M\omega^2r^2-\Omega L_z \quad ; \quad \frac{(\vec{p}-\vec{A})^2}{2M} \qquad \vec{A}=M\vec{\Omega}\times\vec{r}$$

Macroscopically degenerate ground state for the one-body hamiltonian

Same physics as for a charged particle in a magnetic field: Landau levels, etc.

Entering the world of strongly correlated states

Total angular momentum > N^2 ⟺ Number of vortices > Number of atoms

This could be achieved experimentally for small number of atoms: 10 to 100

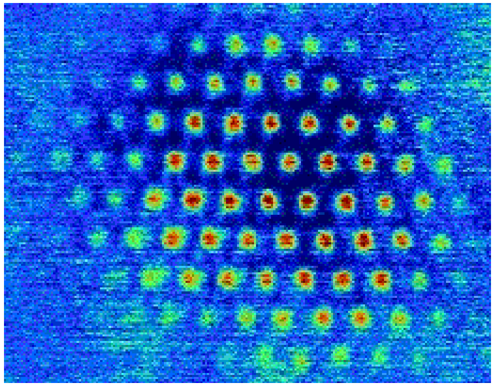
At this stage the mean-field approach breaks down and the ground state of the system is a correlated state:

$$\Psi(\vec{r}_1, \ldots, \vec{r}_N) \neq \phi(\vec{r}_1) \ldots \phi(\vec{r}_N)$$

For some specific filling factors $\nu = \dfrac{N}{N_v}$ the ground state is separated from the excited states by an energy gap: Laughlin-type wavefunction

Fractional Quantum Hall type regime

"Schrödinger cat" states



Consider a single site, with N (between 10 and 100) two-level atoms

b

a

$$|a\rangle^{\otimes N} \xrightarrow{\pi/2 \text{ pulse}} \left(\frac{|a\rangle + |b\rangle}{\sqrt{2}} \right)^{\otimes N}$$

If a-b interactions differ from a-a and b-b, then one can achieve after a given time:

$$\longrightarrow \frac{1}{\sqrt{2}} \left(|a\rangle^{\otimes N} + |b\rangle^{\otimes N} \right)$$

Test of quantum mechanics (decoherence theory), useful for atom interferometry

2.

Condensed matter systems with dilute gases

Spatial density n: 10^{12} to 10^{15} atoms/cm^3

$\longrightarrow$ interatomic distance d between 100 nm to 1000 nm

$d >>$ atomic size but…

$d : \lambda_{dB}$: quantum degenerate gas

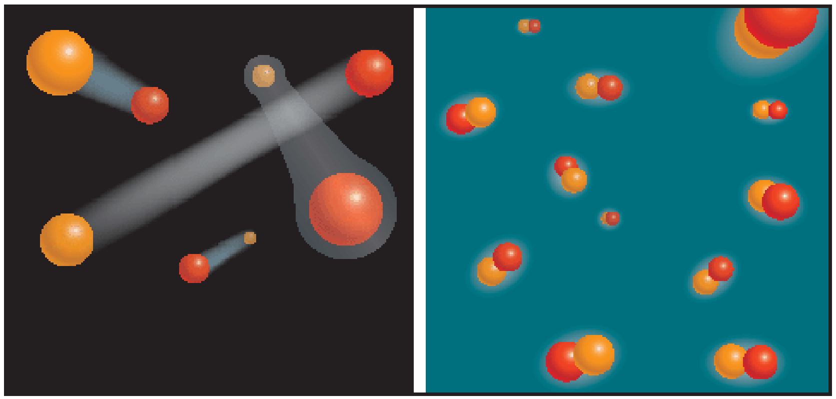
possibly: $d : a$ where a is the scattering length: strongly interacting system

Fermionic atoms: BEC-BCS cross over

→ If only one spin component is present, the gas is ideal at these very low temperatures: the perfect tool for metrology

→ If two spin components (or more) are present, interactions are back.

« Bardeen, Cooper, Schrieffer » side



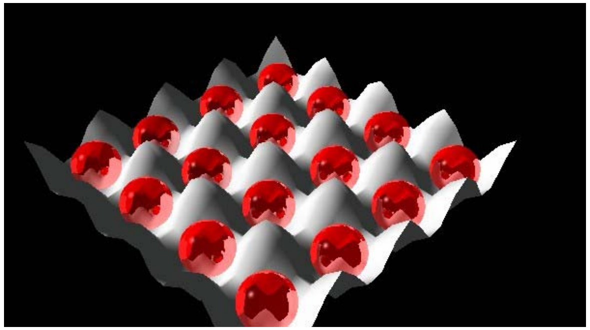
molecular BEC side (easier to study than with bosonic atoms)

Interaction strength

$a < 0$ $a > 0$

$|a| = \infty$

The Mott insulator state

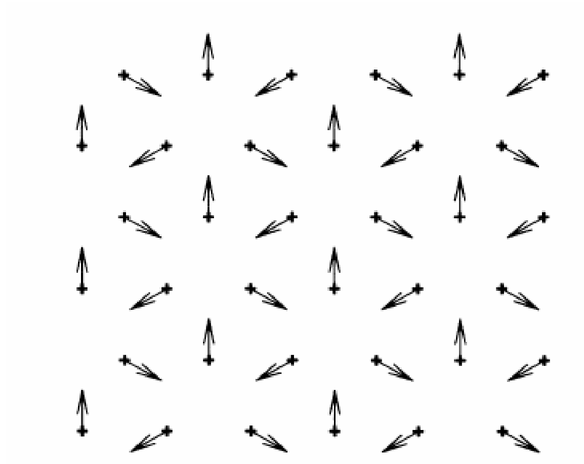


For repulsive interaction between atoms,
the lattice is filled with exactly one atom per site

Antiferromagnetism and frustration

- Study of the Néel phase transition between paramagnetic and antiferromagnetic states for repulsive interaction in a square lattice.

- Frustration in a triangular lattice (long debated question of the presence or absence of planar antiferromagnetic order at T=0 and phase transition at finite T)



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Other topics in relation with condensed matter problems

- **Disordered systems:**
  disordered potential obtained by imaging speckle patterns on a cold atom sample
  Anderson localization of matter waves in the regime of weak interaction

- **Fermi-Bose mixtures**
  instabilities and collapses for attractive fermion-boson interactions
  fermion-boson pairing into fermionic composite

^{40}K ^{7}Li ^{133}Cs ^{6}Li ^{40}K ^{87}Rb ^{6}Li ^{23}Na

- **Reduced dimensionality**
  Fermionisation of the bosons in a 1D Tonks-Girardeau gas
  Rich variety of quantum phases in boson-fermion mixtures in periodic or random potentials

- **Topological potentials**
  Possibility to apply on these systems effective non-Abelian gauge fields using proper laser configurations with multi-level atoms